New evidence for active talus-foot rock glaciers at Øyberget, southern Norway, and their development during the Holocene

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New evidence for the Holocene development of active talus-foot rock glaciers at Øyberget, southern Norway

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Abstract

Synthetic aperture radar interferiometry (InSAR) demonstrates that lobate, blocky depositional landforms at Øyberget, located ~1000 m below the lower climatic limit of discontinuous permafrost in Ottadalen, southern Norway, are active rock glaciers. Five years of InSAR data for six lobes demonstrate average surface movement of 1.2-22.0 mm/year with maximum rates of 17.5-55.6 mm/year. New Schmidt-hammer exposure-age dating (SHD) of two proximal lobes reveals mid-Holocene ages (7.6 ± 1.3 and 6.0 ± 1.2 ka), which contrast with the early-Holocene ages obtained previously from distal lobes, and late-Holocene SHD ages presented here from two adjacent talus slopes (2.3 ± 1.0 and 2.4 ± 1.0 ka). Although passive transport of boulders on the surface of these small, slow-moving rock glaciers means that the exposure ages are close minimum estimates of the time elapsed since lobe inception, disturbance of boulders on fast-moving rock glaciers is a source of potentially serious underestimates of rock-glacier age. Rock-glacier development at Øyberget began shortly after local deglaciation around 10 ka and continued throughout the Holocene in response to microclimatic undercooling within the coarse blocky surface layer of the talus and rock-glacier lobes. Undercooling is inferred to produce a negative thermal offset of ~7 °C, which would be sufficient to develop sporadic permafrost at the site and also to delay fast thawing of rock glaciers in a warming climate. Our results point to circumstances where rock glaciers may be poor indicators of regional climate and of limited usefulness in palaeoclimatic reconstruction.

Key words: talus-derived rock glacier, rock-slope failure, permafrost, active and relict landforms, SAR interferiometry, Schmidt-hammer exposure-age dating, Norway

Introduction

The lobate rock glaciers in Øybergsurdi, located beneath the south-facing rock wall of Øyberget, upper Ottadalen, southern Norway (Figs 1a and 1b) are of significance for several reasons. First, rock glaciers are relatively rare in southern Norway. In their inventory, Lilleøren and Etzelmüller (2011) recognize 241 rock glaciers in Norway, of which just 35 (<10%) are located in the south of the country (not including those at Øyberget).

Second, Ballantyne (2018, p. 316) has disputed the existence of rock glaciers at Øyberget and regards them instead as rockslide runout deposits, as has been proposed for most, if not all, supposed rock glaciers in the British Isles (Ballantyne et al., 2009; Wilson, 2009; Jarman et al., 2013). If his interpretation is correct, there are implications for the identification of rock glaciers in Scandinavia and elsewhere, not only for the landforms at Øyberget.

Third, rock glaciers are generally considered to be reliable indicators of a permafrost environment (Haeberli, 1985; Barsch, 1996; Haeberli et al., 2006; Berthling, 2011; Lilleøren et al., 2012; Kääb, 2013; Ballantyne, 2018), yet those at Øyberget occur at ~530 m above sea level, which is ~1000 m below the present estimated lower altitudinal limit of discontinuous permafrost in this region of southern Norway (Etzelmüller and Hagen, 2005; Lilleøren et al., 2012; Gisnås et al., 2016). The Øyberget rock glaciers must therefore be either relict, or active at an exceptionally low altitude. The preferred conclusion from our previous exposure-age dating studies at the site using both the Schmidt hammer (Matthews et al., 2013) and cosmogenic nuclides (Linge et al., 2020) was that these rock glaciers formed and became relict (inactive) in the early Holocene, shortly after regional deglaciation.

The aim of this short paper is to re-evaluate the status, development and implications of the Øyberget rock glaciers in the light of new evidence. We apply synthetic aperture radar interferiometry (InSAR) from the Norwegian Geological Survey database (http://insar.ngu.no), which demonstrates present-day rock-glacier creep at the site, and effectively disproves both the 'rockslide' and 'relict' hypotheses. This evidence is supported by further exposure-age dating with the Schmidt hammer on proximal rock-glacier lobes and adjacent talus, which has yielded significantly younger dates than the previously dated distal lobes. In combination, the new evidence indicates rock-glacier development at Øyberget throughout the Holocene. Our revised interpretation has important implications for understanding the climatic significance of rock glaciers and for exposure-age dating in the rock-glacier context.

Øyberget rock glaciers and the environmental context

Rock-glaciers occur at ~500-560 m a.s.l. at the foot of extensive ~200-m high talus slopes (gradient 32-36°) that lie beneath the ~400-m high south-facing rock wall of Øyberget (Fig. 1a). The best developed landforms (numbered 1-3), which were investigated and dated previously by Matthews et al. (2013) and Linge et al. (2020), extend ~200 m from the foot of the talus and have the characteristic lobate shape of talus-foot rock glaciers. These lobes have steep (up to 40 °) distal slopes that stand up to 20 m above the surrounding terrain. The upper surfaces of the lobes undulate and have a few transverse ridges (gradients <8°).

All upper surfaces are composed of openwork large boulders (typical long axes 1-3 m; maximum 7 m). Talus boulders are of a similar size. Abutting the foot of the talus, narrower ledge-like lobes occur which, in a few places, have unstable distal slopes that reveal finer sedimentary material beneath the openwork boulders (Fig. 1b). Recent quarrying has revealed similar fine sediment in the toe of lobe 1. Although the rock glaciers are surrounded by Scots pine (*Pinus sylvestris*) forest, only scattered stunted trees grow from crevices between the boulders on the upper surface of some of the lobes. Lichens are typically present on most boulders but mosses and heath plant species are confined to patches of very thin soil in small depressions on boulder surfaces. Almost all boulders are firmly wedged together in the landform and perched boulders are rarely present.

Rocks in the region are mainly Precambrian gneiss (Lutro and Tveten, 1996). The Øyberget rock wall and the boulders in the rock glaciers are banded gneiss with distinctive layers of pink potassium feldspar, grey biotite-mica, and white quartz-feldspar. Complex northward-dipping banding in the rock wall would be expected to be relatively stable in relation to major rock-slope failure while being susceptible to frost weathering and supplying rockfall debris to the talus slopes and hence the rock glaciers.

Climatic normal data (AD 1961-1990) from Gjeilo-i-Skjåk meteorological station (378 m a.s.l.; 20 km down valley), adjusted for an altitudinal lapse rate of 0.65°C per 100 m, indicate a mean annual air temperature at the rock-glacier site of +1.6 °C (Aune, 1993). The corresponding mean January and mean July temperatures are –10.2 °C and +12.9 °C, respectively. Mean annual precipitation from the Gjeilo station is 295 mm, with a July maximum (Førland, 1993), which reflects the strong rain-shadow effect in this area of inland southern Norway. Modelled snow-depth data for the same period (http://www.senorge.no) indicate a maximum snow depth of only 38 mm in March. Although the precipitation and snow depth values may be a little higher at the site of the rock glaciers, they remain extremely low. More detailed climatic information is tabulated in Matthews et al. (2013) and Linge et al. (2020), and is available from eKlima (http://sharki.oslo.dnmi.no).

Deglaciation at the site of the Øyberget rock glaciers occurred at a time of rapid ice-sheet downwastage in the early Holocene. Local evidence, based on ^{10}Be surface-exposure ages from the summit of Øyberget and from the valley floor ~2.0 km up-valley from the rock glaciers (Fig. 1a) was presented and discussed in the regional context by Linge et al. (2020). Corrected ^{10}Be mean age (analytic uncertainty $\pm 2\sigma$) of summit samples was 11.2 ± 0.8 ka and of valley-floor samples was 10.1 ± 0.8 ka. These results are consistent with cosmogenic dating within the broader region (Goehring et al., 2008; Marr et al., 2018, 2019; Andersen et al., 2019), and with large-scale but less precise estimates based on deglaciation modelling in Scandinavia (Hughes et al., 2016; Stroeven et al., 2016). They also justify the ~9.7 ka deglaciation age used previously by Matthews et al. (2013) for Schmidt-hammer exposure-age dating of the rock glaciers close to the valley floor.

Previous investigation of the Øyberget rock glaciers has focused on exposure-age dating of boulders sampled from the surfaces of lobes 1-3 (Fig. 1a and 1b). Based on samples of 150 boulders, Schmidt-hammer exposure-age dating yielded ages ($\pm 2\sigma$)

of 10.3 ± 1.3, 9.9 ± 1.4, and 9.0 ± 1.7 ka, respectively (Matthews et al. 2013). Based on ^{10}Be surface-exposure dates obtained from three boulders on lobe 2 and four boulders on lobe 3, Linge et al. (2020) obtained corrected mean ages of 11.2 ± 1.4 and 11.1 ± 2.4 ka (analytical uncertainty ±2σ), respectively. Taking account of the uncertainties, the two techniques have therefore produced consistent results. The techniques estimate, in different ways, the lapse of time since the boulders were first exposed to the atmosphere. Interpretation of the early-Holocene exposure ages in relation to the formation and development of the rock glaciers is discussed below.

New evidence

InSAR data

New evidence based on synthetic aperture radar interferiometry (InSAR) has recently become available from the Norwegian Geological Survey database (http://insar.ngu.no). InSAR Norge measures deformation of the Earth's surface as one-dimensional velocities along the line-of-sight from satellite sensor to ground surface. These data are particularly appropriate for exposed rock surfaces and are particularly sensitive to vertical movements. Measurements are made from early June to late September to avoid snow-cover effects. Data are available for particular points, which are displayed on maps at variable scales, and groups of points can be selected to define the average movement of specified areas of terrain, such as rock-glacier surfaces. Time series of individual points and groups of points can also be analysed and visualised graphically. Temporal coherence, for which a value of zero equals pure noise and a value of 100 % is noise free, provides a measure of the reliability of data points.

Mean velocity is negative (indicating reduced elevation and downslope movement) for almost all measurement points on the rock-glacier surfaces over the last five years (2015-2019) (Fig. 1c). Over the same period, almost all points from the surrounding terrain, including the talus slopes and the Øyberget rock wall, recorded zero velocity. In order to eliminate anomalous points and obtain representative mean values for lobe surfaces, mean velocity was calculated for large clusters of points from the fastest moving areas of each of lobes 1, 1*, 2, 2*, 3, 3* and 4 (Table 1), as exemplified for lobes 2, 2*, 3 and 3* in Fig. 2. Other clusters of points that exhibit relatively low but significant negative velocity values (west of lobe 1, and both west and east of lobe 2; Fig. 1c) appear to indicate incipient lobes.

Lobes 2, 2* and 3* are the most active with a representative velocity of –15 to –22 mm/year, while lobe 3 (representative velocity –1.2 mm/year) shows one very small area of activity. Lobes 1, 1* and 4 show intermediate levels of activity (representative velocity –10 to –12 mm/year). Maximum velocity recorded over the five-year period at individual points is considerably higher for all measured lobes, ranging between –17.5 (L 1*) and –55.6 mm/year (L 3*). Considering the velocity of distal (1-3) and proximal (1*-3*) lobes in their respective matched pairs, the latter are moving consistently faster than the former. Movement values exhibit near-linear trends through time, as exemplified in Figs 3a-d, with consistent patterns within and between years and temporal coherence values of >70 % for all lobes (Table 1).

In summary, with the exception of L 3, representative InSAR surface velocities of the rock glaciers lie between –10 and –22 mm/year with consistent rates of movement over the five-year monitoring period. Some lobes are moving faster than others.

Schmidt-hammer exposure-age dating (SHD)

The second line of new evidence is from SHD applied to three rock-glacier lobes (L1*, L2* and L3*) located between lobes L1, L2 and L3 and the adjacent talus slopes (Figs 1 and 2). The measurement techniques and approach to age-calibration followed those used previously by Matthews et al. (2013) to date lobes L1-L3. R-values (rebound values) were obtained using 'type-N' mechanical Schmidt hammers (Proceq, 2004) from 150 boulders from the distal (outer) part of the surface of each lobe and from near the foot of each talus slope. Five impacts were made on different points of each boulder resulting in a mean R-value based on 750 individual impacts from each surface. Quartzitic veins, boulder edges and cracks, and wet, steeply sloping and lichen-covered surfaces were avoided. As a precaution against instrument deterioration during use, frequent tests were made on the manufacturer's test anvil. The age-calibration equation of Matthews et al. (2013), based on local control points, was used to produce surface exposure-age estimates. Confidence intervals (*Cc*; 95 %) are based on combining the error of the calibration curve (*Cc*) with the sampling error (*Cc*), using the method developed by Matthews and Owen (2010), Matthews and Winkler (2011), and Matthews and McEwen (2013).

Schmidt-hammer results obtained from two of the proximal lobes (L2* and L3*) are mid-Holocene in age (7.6 ± 1.3 and 6.0 ± 1.2 ka, respectively) and are significantly younger than the early-Holocene ages obtained from the distal lobes (Table 2 and Fig. 4). Their R-value distributions are more platykurtic and L2* exhibits bimodality (Fig. 5). These features indicate mixed-age populations of boulders that differ from the near-normal, unimodal distributions of the distal lobes (particularly L1) and, especially, the older control surface. The age obtained from L1* (11.3 ± 1.3 ka) is, however, significantly older than the other proximal lobes and comparable with the ^{10}Be cosmogenic dates of 11.2 ± 1.4 and 11.1 ± 2.4 ka obtained by Linge et al. (2020) for distal lobes L2 and L3, respectively.

Two of the talus slopes (T2 and T3) yielded late-Holocene ages (2.4 ± 1.0 and 2.3 ± 1.0 ka, respectively) that are significantly younger than those of any of the rock-glacier lobes (Fig. 4). One talus site (T1) is significantly older than the other two talus sites, and does not have the unimodal and leptokurtic distribution of either T2 and T3 or the younger control surface (Fig. 5). Again, this suggests T1 is characterised by a mixed-age population of boulders. Thus, six of the Schmidt-hammer exposure ages exhibit a remarkably consistent temporal pattern with underlying unimodal distributions that are approximately normal and signify single-age populations. Indeed, three pairs of sites (L2 and L3, L2* and L3*, and T2 and T3) have yielded significantly different ages between pairs according to the confidence intervals, whereas within-pair differences are not significantly different (Fig. 4). The common characteristic of the three remaining ages that do not conform to this pattern (L1, L1* and T1*) is that they have each yielded the oldest ages in their respective categories, a possible explanation for which is a systematic difference in the stability of the Øyberget rock wall towards its western end.

In summary, two of the three proximal rock-glacier lobes have yielded mid-Holocene SHD ages that are younger than the three previously-dated early-Holocene distal lobes. Two of the three talus-slope sites date from the late Holocene and are significantly younger than all the rock-glacier sites,

Discussion

Active rock glaciers versus relict rock-slope failures

Identification of rock glaciers and distinguishing them from rock-slope failures and other boulder-dominated landforms is a controversial interpretive problem in geomorphology. The problem arises from the possibility of similar morphologies arising from different formative processes; that is, it is an example of landform mimicry or equifinality (Haines-Young and Petch, 1983; Schumm, 1993; Bevan et al., 1996; Wilson, 2009; Knight et al., 2019). Rock glaciers and rock-slope failures are both coarse-debris deposits located at the foot of steep mountain slopes, which can appear remarkably similar in relation to size, surface features and composition.

Initial recognition of the Øyberget distal lobes as talus-foot rock glaciers was based on several morphological criteria (Matthews et al., 2013), including: (1) the lack of scars or indentations in the Øyberget rock wall that would indicate the source of large-scale rock-slope failures; (2) the relatively uniform boulder size pointing to the piecemeal addition of rockfall material rather than the failure of major sections of the rock wall; (3) the small scale of the lobes relative to the height of fall and hence potential run-out distance likely to be generated following failure of the rock wall; and (4) the integrity of the lobes, their steep distal slopes and transverse ridges, all of which are features consistent with rock-glacier creep. These criteria are not, however, definitive.

The same recognition/equifinality problem has been recently rehearsed in the British Isles where, after several decades of identifying relict rock glaciers (e.g. Dawson, 1977; Chattopadhyay, 1984; Wilson, 1990a, 1990b; Maclean, 1991) many have been re-interpreted as rock-slope failures and a consensus appears to have been reached that there are no *bona fide* rock glaciers (Wilson, 2004, 2009; Harrison et al., 2008; Ballantyne et al., 2009; Jarman et al., 2013). Instead, the landforms previously recognised as rock glaciers have been, almost without exception, firmly identified as rock-slope failures.

In contrast, there are numerous rock glaciers in Norway: of the 241 included in the inventory of Lilleøren and Etzelmüller (2011), most are talus-derived or talus-foot features. However, rock glaciers are uncommon in southern Norway, where only 23 talus-foot rock glaciers were recognised by Lilleøren and Etzelmüller (2011). Ballantyne (2018, p. 316) has claimed that the Øyberget rock glaciers are misinterpreted rockslides, and Wilson et al. (2020) have argued that a boulder-dominated landform assemblage in Alnesdalen, previously mapped as a rock glacier by Sollid and Kristiansen (1984), is mainly the product of one or more rock-slope failures (though attribution of part of this feature to a rock-glacier origin could not be rejected). Apart from these two exceptions, the problem of differentiating rock glaciers from rock-slope failures appears not to have been addressed in Norway.

At Øyberget, the InSAR evidence of movement (Table 1; Figures 1c and 2) is unequivocal in demonstrating that the talus-foot lobes are currently active. As such we consider them to be active rock glaciers rather than relict rock-slope failures. Representative velocities of ~10-20 mm per year and the maximum velocity of ~50 mm per year are low in comparison to measured rates of creep of active rock glaciers elsewhere, even for ‘cold’ polar rock glaciers (Kääb et al., 2002; Bollmann et al., 2015; Ballantyne, 2018). Considerable variations in seasonal and annual rates of movement of rock glaciers occur in response to climate, involving both the thermal regime and precipitation (Kääb et al., 2007; Serrano et al., 2010; Cicoira et al., 2019). It should not be assumed, therefore, that the movement rates derived from InSAR over the five-year monitoring period are applicable to the past.

The sequential increase in exposure age from the talus slopes, through the proximal lobes to the distal lobes is also convincing evidence against a rock-slope failure origin for the Øyberget lobes. Several studies have demonstrated consistent patterns of increasing SHD age of boulders down the axis of relatively long rock-glacier tongues (Frauenfelder et al., 2005; Kellerer-Pirklbauer et al., 2008; Böhlert et al., 2011; Rode and Kellerer-Pirklbauer, 2012; Winkler and Lambiel, 2018). Such patterns are clearly inconsistent with the synchronous surface of deposits formed as a result of rock-slope failure, the debris of which would be of uniform age. However, previous exposure-age dating of the distal lobes yielded only early-Holocene ages (Matthews et al., 2013; Linge et al., 2020). In the absence of dates from proximal lobes and of InSAR data, this led to these authors’ incorrect conclusion that the Øyberget rock glaciers have synchronous surfaces and are relict.

Formation and development of rock glaciers

SHD provides estimates of the average exposure age of the boulders on the rock-glacier surface. At least two generations of lobes are indicated from the SHD results (Table 2 and Figure 4). First, the boulders on the surface of the distal lobes with average ages of 9.0-10.3 ka must have been deposited on the rock-glacier surface in the early Holocene and appear to have been transported passively with only minimal disturbance since then. These inferences are supported by the results of ^{10}Be exposure-age dating of individual boulders from the same lobes (Linge et al., 2020). Rates of movement of 10-20 mm per year from the InSAR data are sufficient, moreover, to account for the development of small lobes of length 100-200 m over a period of ~10 ka. Second, the exposure ages of ~6.0-7.6 ka obtained from two of the proximal lobes indicate somewhat later development, which is compatible with the faster InSAR velocities recorded from these lobes (especially the fastest moving lobe L3*).

Exposure-ages of 2.3-9.0 ka obtained from the talus slopes indicate that whereas some of the talus is much younger than the rock-glacier lobes (and remains active today), other parts date from the early Holocene and are of comparable age to the lobes. The scale of the talus slopes suggests, moreover, that much of the talus volume is likely to have accumulated in the early Holocene when, shortly after deglaciation at ~10 ka, boulder supply from the Øyberget rock wall initiated distal lobe formation. Development of the lobes may therefore have benefited from enhanced (paraglacial) debris inputs from the rock wall following glacial unloading and debuttressing (cf. Cossart et al., 2008; McColl, 2012; Ballantyne et al., 2014; Deline et al., 2015).

The development of the rock-glacier lobes requires not only sufficient debris supply but also cohesive flow of perennially frozen ice-rock mixtures (permafrost creep). This, in turn requires reduction of internal friction and the build-up of cohesion within the talus by excess ice (ice supersaturation) beyond the pore space of the rock particles (Haeberli et al., 2006). On account of the relatively low altitude (~530 m a.s.l.) of the Øyberget lobes, *regional* climatic conditions today are not conducive to permafrost development. The present lower limit of discontinuous permafrost in this region of southern Norway is estimated to lie at ~1500 m a.s.l. (Etzelmüller and Hagen, 2005; Gisnås et al., 2016), probably higher at this south-facing locality. In addition, such regional permafrost limits are unlikely to have been greater than a few hundred metres lower than at present at any time during the Holocene (Lilleøren et al., 2012). The presence of rock-glaciers in such an apparently inauspicious location therefore requires suitable *local* environmental conditions for development of (1) a persistent subsurface permafrost thermal regime and (2) sufficient excess ice within the sedimentary voids.

There have been notable observations of permafrost in coarse blocky openwork deposits such as blockfields, talus and rock glaciers, where mean air temperatures appear too high for its development (Juliussen and Humlum, 2008; Sawada et al., 2003; Stiegler et al., 2014; Morard et al., 2010; Popescu et al., 2017). Indeed, Zacharda et al. (2007) have reported patchy permafrost-like conditions in central European talus where the mean annual air temperature is 6.8–7.5 °C. A negative thermal offset of this scale is sufficient to account for the presence of permafrost in the talus-foot rock glaciers ~1000 m below the lower altitudinal limit of discontinuous permafrost at Øyberget.

Various microclimatic mechanisms have been proposed to explain the thermal offset associated with the coarse surface layer of rock glaciers with or without a winter snow cover (Ballantyne, 2018; Jones et al., 2019; Wagner et al., 2019; Wicky and Hauck, 2020). The mechanisms involve heat exchange by advection and/or convection in the interconnected void spaces between boulders, conduction through the boulders themselves, or thermal radiation. The most cited mechanisms, which include 'Balch ventilation' (Balch, 1900; Humlum, 1997; Harris and Pedersen, 1998) and the 'chimney effect' (Hanson and Hoelzle, 2004; Delaloye and Lambiel, 2005; Kellerer-Pirklbauer et al., 2015), involve cold, dense air displacing warmer air from the void space in winter. We propose that one or more of these mechanisms promote and maintain a subsurface permafrost thermal regime within the Øyberget rock glaciers, assisted by the very low air temperatures and thin snow cover. In effect, the cold winters in this region of southern Norway compensate for quite extreme summer warmth.

Groundwater, rain and snow meltwater are possible sources of liquid water necessary for excess ice development within the Øyberget rock-glacier lobes under a negative mean annual ground temperature regime (cf. Haeberli and Vonder Mühll, 1996). Rain from the summer and autumn rainfall maximum, and meltwater from winter snowfall, including snow deposited on the talus slopes from snow-avalanches (cf. Humlum et al., 2007), are likely to be the most important sources. However, no observations or geophysical evidence relating to the nature of the ice within the Øyberget lobes are available. The hypothesis favoured previously that, following deglaciation, residual glacier ice may have been buried by paraglacial debris accumulation at the base of the Øyberget rock wall, and that this may have triggered rock-glacier formation (Matthews et al., 2013; Linge et al., 2020), is considered unnecessary. Thus, the new evidence presented in this paper has led to what is essentially a microclimatic hypothesis for rock-glacier inception in the early Holocene with development continuing throughout the Holocene to the present day.

Climatic and dating implications of rock glaciers

Our results from Øyberget demonstrate that active rock glaciers can occur well beyond supposed regional climatic limits owing to the development of microclimatically-induced permafrost. The occurrence of sporadic permafrost at ~1000 m below the lower altitudinal limit of discontinuous permafrost is equivalent to a negative thermal offset of at least ~7 °C. This exposes the limitations on using the distribution of active rock glaciers as climatic indicators, and relict rock glaciers in palaeoclimatic reconstruction (cf. Humlum, 1998). Although not presenting a major problem in areas where rock glaciers are common, and anomalies can be readily identified, azonal cases could be of major importance in regions, like southern Norway, where environments are marginal for rock glaciers. In the context of a warming climate, the same microclimatic processes that create undercooling and enable permafrost development beneath the coarse surface layer of rock glaciers, should render rock glaciers resilient and preserve them from fast thawing during the transition from active to relict (cf. Jones et al., 2019; Wagner et al., 2019).

We have also demonstrated that relatively old exposure ages of boulders on rock glaciers may suggest relict status when in fact the rock glaciers are still active due to largely passive transport of the surface boulders. In general, the exposure age of surface boulders from distal parts of rock glaciers provide minimum estimates of the time elapsed since the boulders were first exposed to the atmosphere. If the rock glacier is small and slow moving (or was slow moving in the case of a relict rock glacier), then boulders are likely to have been little disturbed during transport on the rock glacier surface and hence their exposure age may be a close approximation to rock-glacier age in the sense of the time elapsed since formation began (rock-glacier inception). This is the situation in the case of the rock-glacier lobes at Øyberget, which date from various times within the early and mid Holocene. However, the faster a rock glacier moves the more likely that the boulders will be disturbed during transport, and the greater the likelihood that the exposure age will deviate from the age of the landform. High rates of boulder turnover during transport may lead to gross underestimates of landform age. Once fast-moving rock glaciers with high boulder turnover become relict (cease to move) exposure ages may approximate the lapse of time since stabilisation, rather than landform age.

Conclusion

New evidence from the Øyberget landforms has necessitated re-evaluation of the previous interpretations of Matthews et al. (2013) and Linge et al. (2020) in relation to their nature, status, age, development and implications, and has led to the following conclusions:

(1) The talus-foot lobes are correctly interpreted as rock glaciers: they are not relict rock-slope failures.

(2) InSAR data demonstrate that the rock glaciers are active today with representative surface velocities from six lobes (AD 2015-2019) ranging from 1.2-22.0 mm/year and maximum velocities of 17.5-55.6 mm/year.

(3) SHD demonstrates that two of three proximal lobes are of mid-Holocene age (7.6 ± 1.3 and 6.0 ± 1.2 ka) and two of three adjacent areas of talus are of late-Holocene age (2.3 ± 1.0 and 2.4 ± 1.0 ka). The new results are significantly younger than the previously published SHD and ^{10}Be exposure ages from three distal lobes that indicate early-Holocene ages (up to 11.2 ± 1.4 ka).

(4) Passive transport of boulders on the surface of these small, slowly-moving rock glaciers produces exposure ages that represent close minimum estimates of the time elapsed since rock glacier inception. In contrast, on rapidly-moving rock glaciers, such exposure ages may be gross underestimates of the rock-glacier age due to high rates of boulder disturbance and turnover.

(5) Following (paraglacial) inception of rock-glacier formation shortly after retreat of the Scandinavian Ice Sheet from the site around 10 ka, the evidence indicates that at least two generations of rock-glacier development have occurred during the Holocene.

(6) Development of permafrost at the site, ~1000 m below the present lower climatic limit of discontinuous permafrost, suggests that microclimatic undercooling within the coarse blocky surface layer of the talus and rock-glacier lobes is responsible for a negative thermal offset of at least 7.0 °C. This enables growth in the void space of the excess ice necessary for rock-glacier creep and preserves rock glaciers from fast thawing in a warming climate.

(7) However, undercooling may limit the value of rock glaciers as indicators of regional climate, and hence limit their use for palaeoclimatic reconstruction, especially in regions that are marginal for rock-glacier development.

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References

Andersen JL, Egholm DL, Knudsen MF, Linge H, Jansen JD, Goodfellow BW, Pedersen VK, Tikhomirov D, Olsen J, Fredin O (2019) Pleistocene evolution of a Scandinavian plateau landscape. *Journal of Geophysical Research: Earth Surface* 123, doi.org/10.1029/2018JF004670.

Aune B (1993) *Temperaturnormaler: Normalperiode 1961–90.* Det Norske Meteorologiske Institutt: Oslo.

Balch ES (1900) *Glacièrs; or, Freezing Caverns*. Allen, Lane and Scott: Philadelphia.

Ballantyne CK (2018) *Periglacial Geomorphology*. Wiley: Chichester.

Ballantyne CK, Schnabel C, Xu S (2009) Exposure dating and reinterpretation of coarse debris accumulations ('rock glaciers') in the Cairngorm Mountains, Scotland. *Journal of Quaternary Science* 24, 19-31.

Ballantyne CK, Wilson P, Gheorghiu D, Rodés À (2014) Enhanced rock-slope failure following ice-sheet deglaciation: timing and causes. *Earth Surface Processes and Landforms* 39, 900-913.

Barsch D (1996) *Rock Glaciers: Indicators for the Present and Former Geoecology of High Mountain Environments*. Springer-Verlag: Berlin.

Berthling I (2011) Beyond confusion: rock glaciers as cryo-conditioned landforms. *Geomorphology* 131: 98-106.

Bevan K (1996) Equifinality and uncertainty in geomorphological modelling. In Rhodes BL, Thorn CE (eds). *The Scientific Nature of Geomorphology*. Wiley: Chichester, 289-313.

Böhlert R, Compeer M, Egli M, Brandova D, Maisch M, Kubik PW, Haeberli W (2011) A combination of relative-numerical dating methods indicates two high Alpine rock glacier activity phases after the glacier advance of the Younger Dryas. *The Open Geography Journal* 4, 115-130.

Bollmann E, Girstmair A, Mitterer S (2015) A rock glacier activity index based on rock glacier thickness changes and displacement rates inferred from airborne laser scanning. *Permafrost and Periglacial Processes* 26, 347-359.

Chattopadhyay GP (1984) A fossil valley-wall rock glacier in the Cairngorm Mountains. *Scottish Journal of Geology* 20, 121-125.

Cicoira A, Beutel J, Faillettaz J, Vieli A (2019) Water controls the seasonal rhythm of rock glacier flow. *Earth and Planetary Science Letters* 528, 115844.

Cossart E, Braucher R, Fort M, Bourlés DL, Carcaillet J (2008) Slope instability in relation to glacial debuttressing in alpine areas (upper Durance catchment, southeastern France): evidence from field data and ^{10}Be cosmic ray exposure ages. *Geomorphology* 95, 3-26.

Delaloye R, Lambiel C (2005) Evidence of winter ascending air circulation throughout talus slopes and rock glaciers situated in the lower belt of alpine discontinuous permafrost. *Norsk Geografisk Tidsskrift/Norwegian Journal of Geography* 59: 194-203.

Deline P, Gruber S, Delaloye R, Fischer L, Geertseema M, Giardino M, Hasler A, Kirkbride M, Krautblatter M, Magnin F (2015) Ice loss and slope stability in high-mountain regions. In Haeberli W, Whitman C (eds.) *Snow and Ice-related Hazards, Risks and Disasters*. Amsterdam: Elsevier, 521-561.

Dawson AG (1977) A fossil lobate rock glacier in Jura. *Scottish Journal of Geology* 13, 31-42.

Etzelmüller B, Hagen JO (2005) Glacier-permafrost interaction in Arctic and alpine mountain environments with examples from southern Norway and Svalbard. In Harris C, Murton JB (eds) *Cryospheric Systems: Glaciers and Permafrost*. Geological Society, London, Special Publication 242, 11-27.

Førland EJ (1993) *Nedbørnormaler: Normalperiode 1961–90.* Det Norske Meteorologiske Institutt: Oslo.

Frauenfelder R, Laustela M, Kääb A (2005) Relative-age dating of Alpine rockglacier surfaces. *Zeitschrift für Geomorphologie NF* 49, 145-166.

Gisnås K, Etzelmüller B, Lussana C, Hjort J, Sannel ABK, Isaksen K, Westermann S, Kuhry P. Christiansen H, Frampton A, Åkerman J (2017) Permafrost map for Norway, Sweden and Finland. *Permafrost and Periglacial Processes* 28, 359-378.

Goehring BM, Brook EJ, Linge H, Raisbeck GM, Yiou F (2008) Beryllium-10 exposure ages of erratic boulders in southern Norway and implications for the history of the Fennoscandian Ice Sheet. *Quaternary Science Reviews* 27, 320-336.

Haeberli W (1985) Creep of mountain permafrost: internal structure and flow of Alpine rock glaciers. *Mitteilungen der Versuchsanstalt für Wasserbau, Hydrologie and Glaziologie* 77, 1-142.

Haeberli W, Vonder Mühll D (1996) On the characteristics and possible origins of ice in rock glacier permafrost. *Zeitschrift für Geomorphologie Supplement Band* 49, 145-166.

Haeberli W, Hallet B, Arenson L, Elconin R, Humlum O, Kääb A, Kaufmann V, Ladanyi B, Matsuoka N, Springman S, Vonder Mühll D (2006) Permafrost creep and rock glacier dynamics. *Permafrost and Periglacial Processes* 17, 189-214.

Haines-Young RH, Petch JR (1983) Multiple working hypotheses: equifinality and the study of landforms. *Transactions of the Institute of British Geographers NS* 8, 458-466.

Hanson S, Hoelzle M (2004) The thermal regime of the active layer at the Murtèl rock glacier based on data from 2002. *Permafrost and Periglacial Processes* 15, 273-282.

Harris SA, Pedersen DE (1998) Thermal regimes beneath coarse blocky material. *Permafrost and Periglacial Processes* 9, 107-120.

Harrison S, Whalley B, Anderson E (2008) Relict rock glaciers and protalus lobes in the British Isles: implications for Late Pleistocene mountain geomorphology and palaeoclimate. *Journal of Quaternary Science* 23, 287-304.

Hughes ALC, Gyllencreutz R, Lohne Ø, Mangerud J, Svendsen JL (2016) The last Eurasian ice sheets – a chronological database and time-slice reconstruction, DATED-1. *Boreas* 45, 1-45.

Humlum O (1997) Active layer thermal regime at three rock glaciers in Greenland. *Permafrost and Periglacial Processes* 8, 383-408.

Humlum O (1998) The climatic significance of rock glaciers. *Permafrost and Periglacial Processes* 9, 375-395.

Humlum O, Christiansen HH, Juliussen H (2007) Avalanche-derived rock glaciers in Svalbard. *Permafrost and Periglacial Processes* 18, 75-88.

Jarman D, Wilson P, Harrison S (2013) Are there any rock glaciers in the British mountains. *Journal of Quaternary Science* 28, 131-143.

Jones DB, Harrison S, Anderson K, Whalley WB (2019) Rock glaciers and mountain hydrology: a review. *Earth-Science Reviews* 193: 66-90.

Juliussen H, Humlum O (2008) Thermal regime of openwork block fields on the mountains Elgåhogna and Sølen, central-eastern Norway. *Permafrost and Periglacial Processes* 19: 1-18.

Kääb A (2013) Rock glaciers and protalus forms. In Elias SA (ed) *Encyclopedia of Quaternary Science, volume 3, 2nd edition.* Elsevier: Amsterdam, 535-552.

Kääb A, Isaksen K, Eiken T, Farbrot H (2002) Geometry and dynamics of two lobe-shaped rock glaciers in the permafrost of Svalbard. *Norsk Geografisk. Tidsskrift/Norwegian Journal of Geography* 56, 152-160.

Kääb A, Frauenfelder R, Roer I (2007) On the response of rock glacier creep to surface temperature increase. *Global and Planetary Change* 56, 172-187.

Kellerer-Pirklbauer A, Wangensteen B, Farbrot H, Etzelmüller B (2008) Relative surface age-dating of rock glacier systems near Hólar in Hjaltadulur, northern Iceland. *Journal of Quaternary Science* 23, 137-151.

Kellerer-Pirklbauer A, Pauritsch M, Winkler G (2015) Widespread occurrence of ephemeral funnel hoarfrost and related air ventilation in coarse-grained sediments of a relict rock glacier in the Seckauer Tauern Range, Austria. *Geografiska Annaler Series A (Physical Gegraphy*) 97, 453-471.

Knight J, Harrison S, Jones DB (2019) Rock glaciers and the geomorphological evolution of deglacierizing mountains. *Geomorphology* 324, 14-24.

Lilleøren KS, Etzelmüller B (2011) A regional inventory of rock glaciers and ice-cored moraines in Norway. *Geografiska Annaler Series A (Physical Geography)* 93, 175-191.

Lilleøren KS, Etzelmüller B, Schuler TV, Gisnås K, Humlum O (2012) The relative age of mountain permafrost – estimation of Holocene permafrost limits in Norway. *Global and Planetary Change* 92-93, 209-223.

Linge H, Nesje A, Matthews JA, Fabel D, Xu S (2020) Evidence for rapid paraglacial formation of rock glaciers in southern Norway from ^{10}Be surface-exposure dating. *Quaternary Research* 97, 55-70.

Lutro O, Tveten E (1996) *Geologisk kart over Norge, bergrunnskart Årdal M 1:250,000.* Norges Geologiske Undersøkelse: Trondheim.

Maclean AF (1991) *The formation of valley-wall rock glaciers*. PhD thesis, University of St. Andrews.

Marr P, Winkler S, Löffler J (2018) Investigations on blockfields and related landforms at Blåhø (Southern Norway) using Schmidt-hammer exposure-age dating: palaeoclimatic and morphodynamic implications. *Geografiska Annaler Series A (Physical Geography)* 100, 285-306.

Marr P, Winkler S, Binnie SA, Löffler J (2019) ^{10}Be-based exploration of the timing of deglaciation in two selected areas of southern Norway. *E&G Quaternary Science Journal* 68, 165-176.

Matthews JA, McEwen LJ (2013) High-precision Schmidt-hammer exposure-age dating (SHD) of flood berms, Vetlestølsdalen, alpine southern Norway: first application and some methodological issues. *Geografiska Annaler, Series A (Physical Geography)* 95, 185-195.

Matthews JA, Owen G (2010) Schmidt-hammer exposure-age dating: developing linear age-calibration curves using Holocene bedrock surfaces from the Jotunheimen-Jostedalsbreen regions of southern Norway. *Boreas* 39, 105-115.

Matthews JA, Winkler S (2011) Schmidt-hammer exposure-age dating (SHD): application to early Holocene moraines and a reappraisal of the reliability of terrestrial cosmogenic nuclide dating (TCND) at Austanbotnbreen, Jotunheimen, Norway. *Boreas* 40, 256-270.

Matthews JA, Nesje A, Linge H (2013) Relict talus-foot rock glaciers at Øyberget, upper Ottadalen, southern Norway. *Permafrost and Periglacial Processes* 24, 336-346.

McColl ST (2012) Paraglacial rock-slope stability. *Geomorphology* 153-154, 1-16.

Morard S, Delaloye R, Lambiel C (2010) Pluriannual thermal behaviour of low elevation cold talus slopes in western Switzerland. *Geographica Helvetica* 65, 124-134.

Popescu R, Vespremeanu-Stroe A, Onaca A, Vasile M, Cruceru N, Pop O (2017) Low-altitude permafrost research in an overcooled talus slope-rock glacier system in the Romanian Carpathians (Detunata Goală, Apuseni Mountains). *Geomorphology* 295, 840-854.

Proceq (2004) *Operating instructions. Betonprüfhammer N/NR-L/LR.* Proceq SA: Schwerzenbach.

Rode M, Kellerer-Pirklbauer A (2012) Schmidt-hammer exposure-age dating (SHD) of rock glaciers in the Schöderkogel-Eisenhut area, Schladminger Tauern Range, Austria. *The Holocene* 22, 761-771.

Sawada Y, Ishikawa M, Ono Y (2003) Thermal regime of sporadic permafrost on a block slope on Mt Nishi-Nupukasushinupuri, Hokkaido Island, northern Japan. *Geomorphology* 52, 121-130.

Schumm SA (1993) *To Interpret the Earth – Ten Ways to be Wrong.* Cambridge University Press: Cambridge.

Serrano E, de SanjoséJJ, González-Trueba JJ (2010) Rock glacier dynamics in marginal periglacial environments. *Earth Surface Processes and Landforms* 35, 1302-1314.

Sollid JL, Kristiansen K (1984) *Raumavassdraget, Kvartaergeologi og geomorfologi, 1: 80,000.* Universitetet I Oslo, Geografisk Institutt.

Stiegler C, Rode M, Sass O, Otto JC (2014) An undercooled scree slope detected by geophysical investigations in sporadic permafrost below 1000 m asl, central Austria. *Permafrost and Periglacial Processes* 25, 194-207.

Stroeven AP, Hätestrand C, Kleman J, Heyman J, Fabel D, Fredin O, Goodfellow W, Harbor JM, Jansen JD, Olsen L, Caffee MW, Fink D, Lundqvist J, Rosqvist GC, Strömberg B, Jansson KN (2016) Deglaciation of Fennoscandia. *Quaternary Science Reviews* 147, 91-121.

Wagner T, Pauritsch M, Mayaud C, Kellerer-Pirklbauer A, Thalheim F, Winkler G (2019) Controlling factors of microclimate in blocky surface layers of two nearby relict rock glaciers (Niedere Tauern Range, Austria). *Geografiska Annaler, Series A (Physical Geography)* 101, 310-333.

Walker M, Head MJ, Berkelhammer M, Björk S, Cheng H, Cwynar L, Fisher D, Gkinis V, Long A, Lowe J, Newnham R, Rasmussen SO, Weiss H (2018) Formal ratification of the subdivision of the Holocene Series/Epoch (Quaternary

System/Period): two new Global Boundary Stratotype Sections and Points (GSSPs) and three new stages/subseries. *Episodes* 41(4), 1-11. DOI:10.18814/episodes/2018/018016.

Wicky J, Hauck C (2020) Air convection in the active layer of rock glaciers. *Frontiers in Earth Science* 8, 335. DOI:10.3389/feart.2020.00335.

Wilson P (1990a) Characteristics and significance of protalus ramparts and fossil rock glaciers on Errigal Mountain, County Donegal. *Proceedings of the Royal Irish Academy* 90B, 1-21.

Wilson P (1990b) Morphology, sedimentological characteristics and origin of a fossil rock glacier on Muckish Mountain, County Donegal, northwest Ireland. *Geografiska Annaler Series A (Physical Geography)* 72A, 237-247.

Wilson P (2004) Relict rock glaciers, slope failure deposits, or polygenetic features? A reassessment of some Donegal debris landforms. *Irish Geography* 37, 77-87.

Wilson P (2009) Rockfall talus slopes and associated talus-foot features in glaciated uplands of Great Britain and Ireland: periglacial, paraglacial or composite landforms? In Knight J, Harrison S (eds) *Periglacial and Paraglacial Processes and Environments*. Geological Society, London, Special Publication 320, 133-144.

Wilson P, Matthews JA, Mourne RW, Linge H, Olsen J. (2020) Interpretation, age and significance of a relict paraglacial and periglacial boulder-dominated landform assemblage in Alnesdalen, Romsdalsalpane, southern Norway. *Geomorphology* 369, 107362.

Winkler S, Lambiel C (2018) Age constraints of rock glaciers in the Southern Alps/New Zealand – exploring their palaeoclimatic potential. *The Holocene* 28, 778-790.

Zacharda M, Gude M, Růžička V (2007) Thermal regime of three low elevation scree slopes in Central Europe. *Permafrost and Periglacial Processes* 18, 301-308.

Table 1. InSAR data for seven rock-glacier lobes at Øyberget. Mean velocity refers to groups of points from each rock glacier (June 2015 to September 2019), maximum

velocity refers to the point with greatest movement, and temporal coherence indicates data quality.

Lobe No.	No. of points	Mean velocity (mm/year)	Maximum velocity (mm/year)	**Temporal coherence (%)**
1	**62**	**–9.5**	**–19.0**	78
1*	**48**	**–12.2**	**–17.5**	79
2	**92**	**–14.5**	**–24.7**	76
2*	**57**	**–17.0**	**–28.9**	70
3	**88**	**–1.2**	**–22.3**	79
3*	**52**	**–22.0**	**–55.6**	72
4	60	–11.3	–30.1	73

Table 2. Schmidt-hammer R-values and exposure-age dates with 95% confidence intervals (*Ct*) for boulder surfaces on rock-glacier lobes (L) and adjacent talus slopes (T) at Øyberget. SD = standard deviation; *Cc* and *Cs* are the age-calibration and sampling components of *Ct*).

Site No.	R-value mean	R-value S.D.	Age (years)	*Ct* (years)	*Cc* (years)	*Cs* (years)	**Source**
L1	**49.28**	**4.90**	**10340**	**±1005**	**720**	**705**	Matthews et al. (2013)
L2	**49.75**	**6.82**	**9920**	**±1385**	**985**	**980**	..
L3	**50.83**	**8.35**	**8965**	**±1680**	**1180**	**1195**	..
L1*	**48.18**	**6.97**	**11310**	**±1305**	**835**	**1000**	This paper
L2*	**52.35**	**7.20**	**7620**	**±1270**	**850**	**1030**	..
L3*	**54.18**	**7.00**	**6000**	**±1220**	**695**	**1005**	..
T1	**50.82**	**6.81**	**8975**	**±1245**	**775**	**975**	..
T2	**58.24**	**5.39**	**2400**	**±980**	**600**	**775**	..
T3	**58.41**	**5.46**	**2250**	**±985**	**600**	**785**	..

Figure captions

Fig. 1. (a) Location map with numbered rock-glacier lobes, areas covered by Figs 1b, 1c and 2, the location of up-valley control surfaces for SHD, and the sites of ^{10}Be cosmogenic sampling up-valley and on the summit of Øyberget. (b) Aerial photograph (https://www.norgeibilder.no/) of the rock glaciers and surroundings. (c) InSAR map of mean velocity for individual points on the rock glaciers and surrounding rock surfaces (http://insar.ngu.no/)

Fig. 2. InSAR map (http://insar.ngu.no/) of mean velocity for individual points on rock-glacier lobes 2, 2*, 3 and 3*. Groups of points used for defining representative mean velocities for each lobe are encircled by dashed lines.

Fig. 3. (a)-(d) Time series of representative mean velocity (groups of points shown on Fig. 2) for rock-glacier lobes 2, 2*, 3 and 3*: InSAR data (http://insar.ngu.no/) June to September, 2015–2019.

Fig. 4. Schmidt-hammer exposure-ages of distal rock-glacier lobes (L1-3), proximal rock-glacier lobes (L1*-3*), and adjacent talus slopes (T1-3). YD = Younger Dryas. Formal subdivisions of the Holocene follow Walker et al. (2018).

Fig. 5. Schmidt-hammer R-value distributions for distal rock-glacier lobes (L1-3), proximal rock-glacier lobes (L1*-3*), adjacent talus slopes (T1-3), and older and younger control points (blue shading). Vertical lines indicate the mean R-values of the older (green) and younger (red) control points, respectively.

****On Fig. 5 T1 (upper right) is labelled as L1.****